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Membrane Vibration Studies Using a Scanning Laser Vibrometer

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ABSTRACT

This paper summarizes on-going experimental work at NASA Langley Research Center to measure the dynamics of a 1.016 m (40 in) square polyimide film Kapton membrane. A fixed fully automated impact hammer and Polytec PSV-300-H scanning laser vibrometer were used for non-contact modal testing of the membrane with zero-mass-loading. The paper discusses the results obtained by testing the membrane at various tension levels and at various excitation locations. Results obtained by direct shaker excitation to the membrane are also discussed.

1. INTRODUCTION

With the increasing interest in large ultra-lightweight space structures and the desire for further exploration and discovery in space, revolutionary concepts for large antennas and observatories, solar sails, inflatable solar arrays and concentrators, and inflatable habitats, are being studied in NASA's Gossamer Spacecraft Initiative[1-3]. These systems will use new, ultra-lightweight materials (e.g., carbon nanotubes and membranes with thicknesses less than 5 microns). In the next few years, prototype hardware will be produced and will require structural testing and validation. To date, only a few experimental studies concerning the vibration of pre-tensioned flat membranes for space structures applications have been performed[4-7]. Their delicate nature requires non-contacting structural measurement techniques. Laser vibrometry is one candidate technology for this purpose.

The research reported in this paper was conducted to begin to address the technical challenges and requirements of modal testing for future ultra-lightweight and inflatable space structures. Specific objectives of this work are to investigate the effectiveness (i.e., accuracy, precision, repeatability, etc.) of laser vibrometer measurements obtained on a thin pre-tensioned flat membrane at various tension levels and using various excitation methods.

2. TEST ARTICLE AND EXPERIMENTAL PROCEDURE

2.1 Description of Test Article

The test specimen used for this study was a 1.016 m (40 in) square polyimide Kapton membrane with a thickness of 0.0508 mm (0.002 in). Figure 1 shows the test configuration for this study. The test article was set in a diagonal configuration to allow for easier mounting of tensioning hardware. Each of the corners of the material were reinforced using 0.12 mm (0.005 in) thick transparency film on both sides. Rubber grommets were used to avoid tearing of the membrane under tension loads. All four corners of the article were tensioned using adjustable turnbuckles. The test article was attached to the turnbuckle with 0.0126 gage wire. Force gauges were used to determine tension at each of the four corners. The tensioning devices were supported by a 2.159 m (85 in) square aluminum frame. A 6.35 mm (0.25 in) clear acrylic plate was placed on the front side of the frame to reduce ambient air currents on the membrane.

2.2 Experimental Procedure

A Polytec PSV-300-H scanning laser vibrometer system was used to measure vibration of the test article. To provide more accurate measurements, 100 retro-reflective dots were adhered to the membrane in a grid pattern at even spacing of 101.6 mm (4 in) to allow for increased reflection of the laser beam to the laser vibrometer. The Polytec software was used to view frequency response functions (FRF's) and operating deflection shapes (ODS's). ME'scope and IDEAS® software were used to perform further analysis.

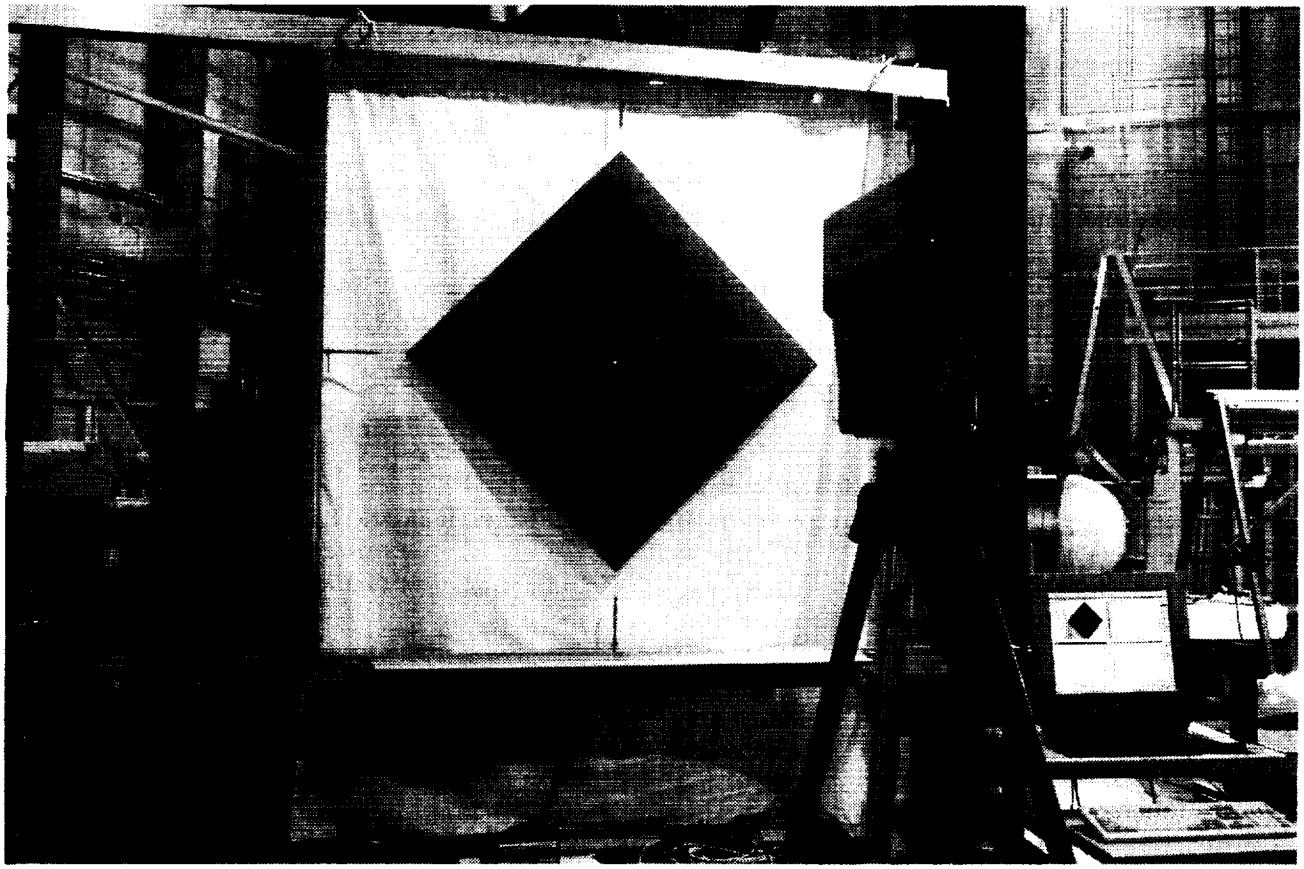

Figure 1: Experimental test setup

The test article was excited using a Piezotronics PCB086B09 impact hammer which was triggered by a digital timer switch box for automated excitation. The hammer was secured to a heavy steel plate set on a table positioned on the backside of the membrane as shown in Figure 2. The impact hammer was used to avoid mass loading of the article and to provide a consistent excitation input force. This excitation method provided an out-of-plane disturbance on the membrane. The hammer location on the membrane was varied to allow for excitation of different modes and to obtain a more complete dynamic model of the membrane. The various hammer locations, shown in Figure 3, included excitation at the corners as well as within the body of the membrane. Tests were performed at a 10 N (2.3 lbf) tension level at locations 2-7. Hammer location number 1 was used to perform tests on the membrane at various tension levels. The FRF's for these tests were computed using 3 ensemble averages and 480 frequency lines from 0 to 30 Hz. The duration of each test was approximately 80 minutes to acquire all 100 FRF's.

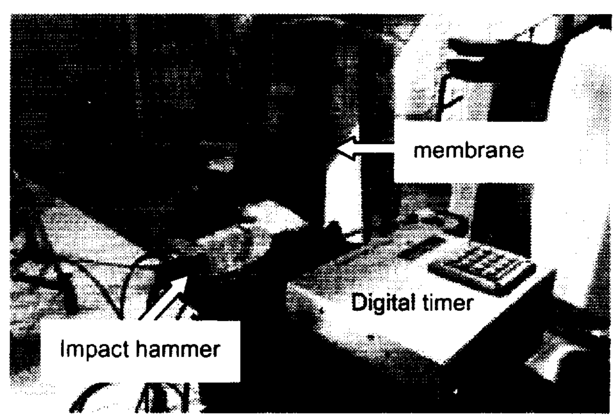

Figure 2: Impact hammer setup

For comparative analysis, a Ling Dynamic Systems V203 electrodynamic shaker was used to excite the lower corner of the membrane. The shaker was placed on the backside of the membrane and used a thin metal stinger to transmit input forces to the test article.

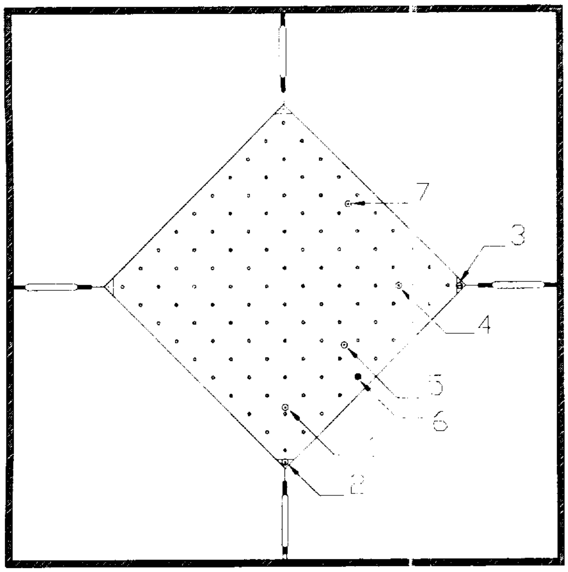

Figure 3: Impact hammer excitation locations

A force gauge was used on the end of the stinger to measure input force. The opposite side of the force gauge was adhered to the membrane as shown in Figure 4. Tests were performed using a pseudo-random signal with a bandwidth of 0 to 100 Hz. The FRF's were computed using 3 ensemble averages and 480 frequency lines from 0 to 30 Hz.

All of the modal tests used highly sensitive 10 lb load cells. The high sensitivity allowed for better resolution of small forces for more accurate FRF's. All of the vibration measurements discussed in this paper were made at ambient temperature and pressure conditions inside the high bay of the structural dynamics laboratory located at the NASA Langley Research Center.

3. RESULTS

3.1 Variation in Impact Hammer Excitation Location

Figure 5 summarizes the dominant frequencies identified by the various impact hammer tests. There was little change in frequency of these modes with variation in excitation location, and the frequency differences that did occur appear to be related to the relatively small variation in membrane tension between tests as shown in Figure 6. The ODS's obtained from excitation location 1 are illustrated in Figure 7. The ODS's are very symmetric, as can be expected given the test configuration, and due to the fact that there was zero mass loading during excitation. Several of the modes could not be excited at locations 5-7 since the excitation was located near a node

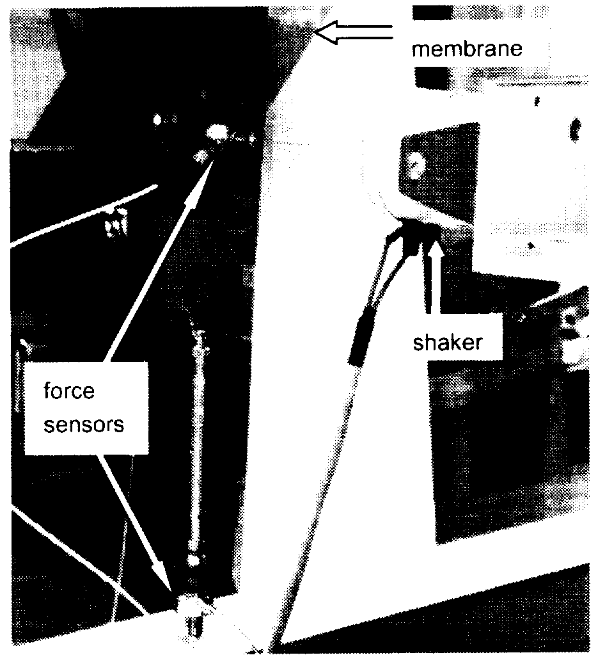

Figure 4: Shaker setup

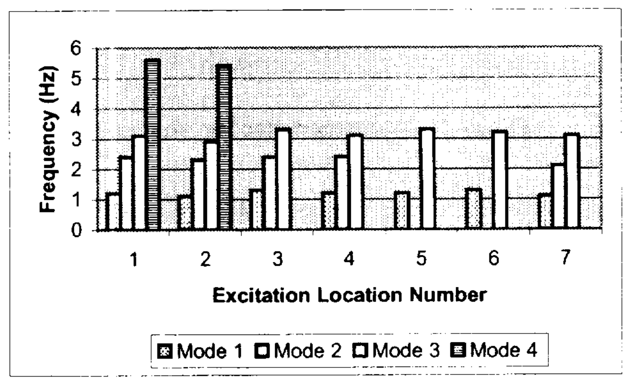

Figure 5: Resonant frequencies (Hz) obtained from excitation locations 1 to 7

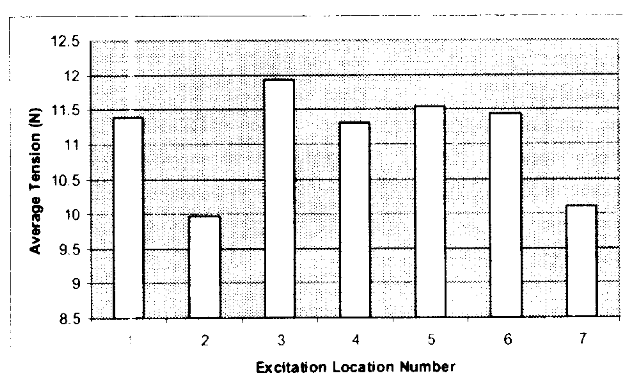

Figure 6: Membrane average tension (N) for each test case

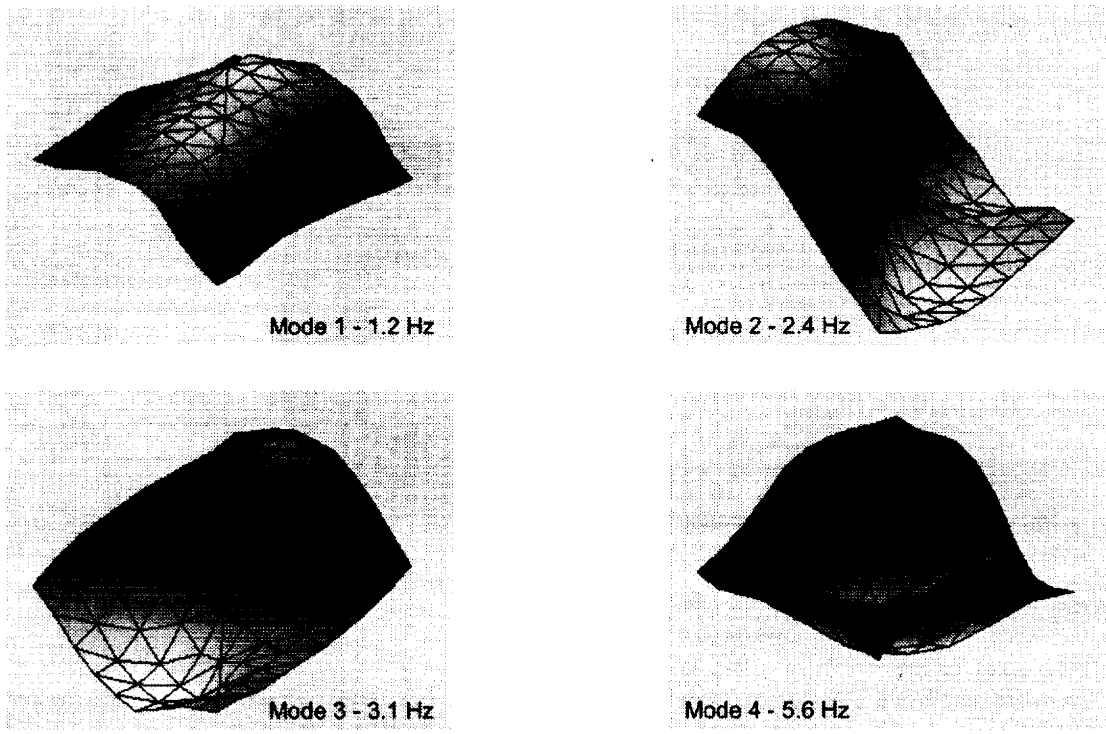

Figure 7: Operating deflection shapes obtained from excitation above lower corner of membrane (#1)

line for these particular modes. Mode 4 could only be excited at the lower corner locations (#1 and #2), however, a similar mode with bending occurring along the other diagonal was excited at the right corner locations (#3 and #4) at about the same frequency. The modal assurance criterion (MAC) was used to assess the degree of correlation of ODS's between the various tests. Figure 8 shows that mode 2 could be consistently excited only at the corner locations (#1, #2, #3, and #4). Mode 1 showed good correlation for all seven tests, while mode 3 showed very poor correlation between all tests. Mode 4 could only be excited at the lower corner locations (#1 and #2), and also showed poor correlation. The differences in the ODS's between tests is probably due to a combination of factors, such as the variation in tension between tests, the non-linear nature of the test article, and sub-optimal excitation.

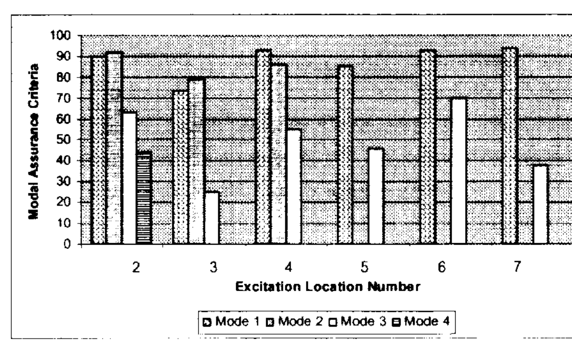

Figure 8: MAC's with respect to modes from test #1

Figure 9 illustrates a strong ODS obtained by exciting the membrane at the lower corner (#2) that could not be well excited at the other locations. The majority of the higher-order modes obtained by excitation at this location (#2) involve ODS's with large deformation at the drive point. Similar ODS's were found for the right corner excitation location (#3). Figure 10 illustrates a strong ODS that could only be identified by exciting the membrane at the edge locations (#6 and #7). Therefore, multiple excitation locations are required to obtain a complete modal model of the membrane.

Figure 11 shows the coherence near the drive point for the test performed with the excitation at the upper right edge of the membrane (#7). The broadband drop in coherence is an indication of non-linear behavior. This

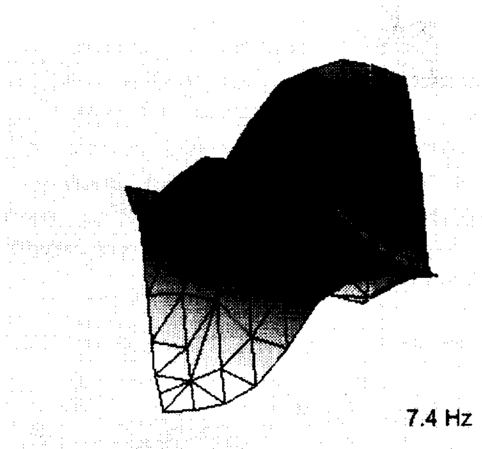

Figure 9: Strong ODS for excitation at lower corner of membrane (#2)

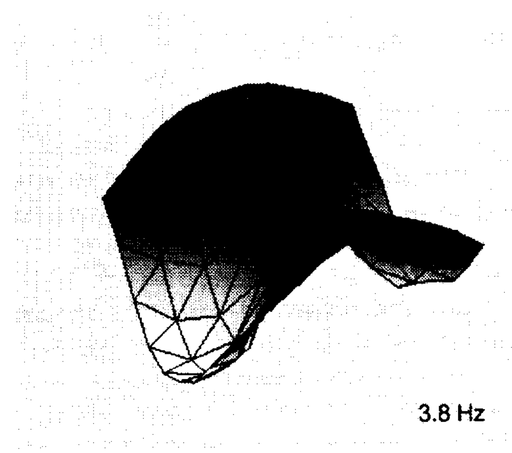

Figure 10: Strong ODS for excitation at right lower edge of membrane (#6)

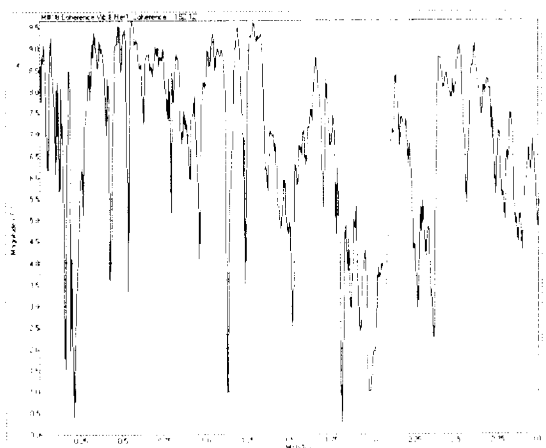

Figure 11: Coherence near drive point for excitation at upper right edge of membrane (#7)

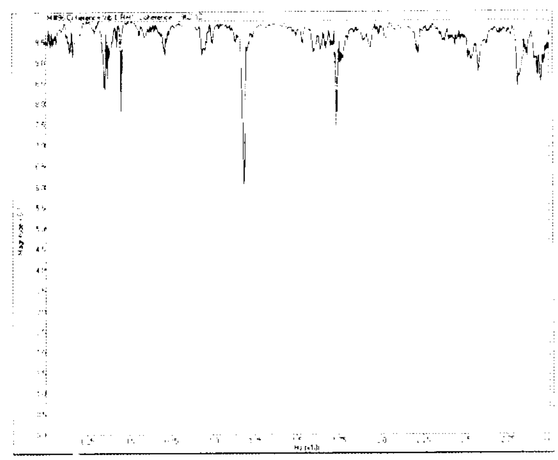

Figure 12: Coherence near drive point for excitation above the lower corner of membrane (#1)

can be expected since the excitation is occurring in a region of low stiffness and high flexibility near the edge of the membrane, where it may exhibit local nonlinear response. Figure 12 shows improved drive point coherence for the test performed with the excitation in the body of the membrane (#1) where the membrane has a higher stiffness than at the edge location.

Figure 13 is a typical FRF that shows the response within the body of the membrane due to excitation at the lower corner (#2). This particular test was able to excite many symmetric, realistic looking ODS's up to about 20 Hz. Many of these ODS's are similar to the one shown in Figure 9 with 2nd order bending along the diagonal, while other ODS's had 1st, 3rd, or 4th order bending along the diagonal. More work is needed to validate the accuracy of these modes.

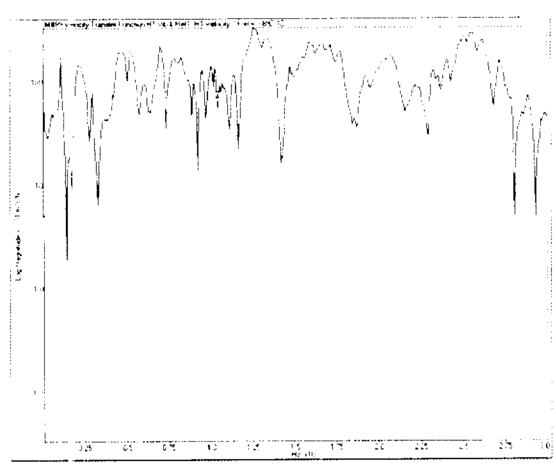

Figure 13: FRF for excitation at lower corner (#2)

3.2 Variation in Tension Loads

A series of impact hammer modal tests were performed with the membrane at the various tension loads shown in Table 1. The tests were conducted with the excitation occurring above the lower corner of the membrane (#1). Figure 14 shows that the three dominant frequencies increase with increasing membrane tension load. All three natural frequencies are shown to increase at approximately the same rate in an approximately linear fashion. Mode 3 (ODS illustrated in Figure 7 at 3.1 Hz) is not shown in Figure 14, because it has a node line near the drive point and could not be consistently excited.

Tension	Units	Tension	Units
5.0	N	1.124	lbf
10.0	N	2.248	lbf
20.0	N	4.496	lbf
30.0	N	6.744	lbf

Table 1: Tension loads

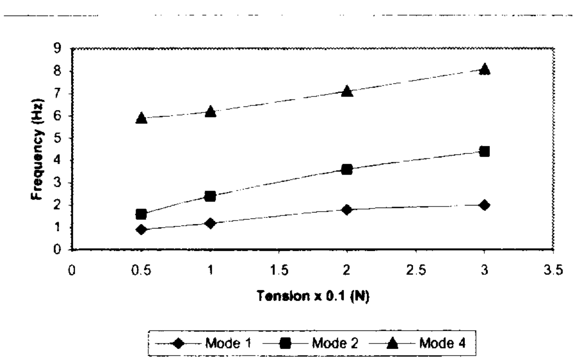

Figure 14: Natural frequency as a function of membrane tension load

3.3 Shaker Test

A shaker test was performed by applying a pseudo-random input to the lower corner of the membrane as described in section 2.2 of this paper. As shown in Figure 15, the FRF's obtained using shaker excitation were noisy. Also, the ODS's were not symmetric as would be expected given the test configuration. The modes may have been affected by the mass and stiffness effects of the shaker attachment through the stinger. Typically, the stinger is used to uncouple the effects of the shaker from the test article by providing low transverse and rotational stiffness. However, in this case coupling effects may occur since even a thin stinger has a relatively high transverse stiffness compared to the membrane. It should be noted that only 3 ensemble averages were used to calculate the FRF's for comparison with impact hammer results. Increasing the averages may reduce the noise in the FRF's, and this will be looked at in the future. Also, additional tests are planned using alternate excitation signals, such as periodic chirp and burst random at various force levels.

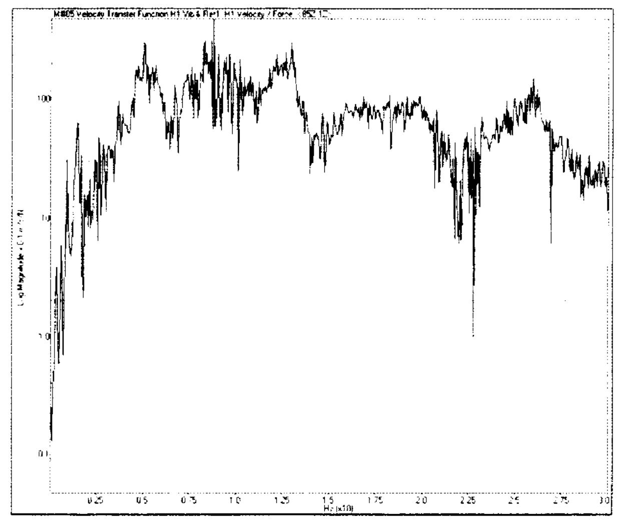

Figure 15: FRF for shaker excitation at lower corner of membrane

4. FUTURE WORK

Future work will focus on characterizing the nonlinear dynamic response of the membrane using constant force sine sweeps, performing modal tests in a vacuum chamber for comparison with ambient atmospheric data to determine air mass and damping effects, experimenting with alternate excitation methods, which may include piezoelectric devices and non-contact magnetic exciters, and correlating test and analysis results.

5. CONCLUSIONS

A fixed fully automated impact hammer and laser vibrometer were used for non-contact modal testing of a thin pre-tensioned membrane with zero-mass-loading. From these tests the following conclusions are drawn:

(i) The resonant frequency of the first four dominant modes varies little with variation in excitation location, and the differences that did occur can be attributed in large part to the variation in membrane tension between tests.

(ii) Only the first two dominant operating deflection shapes (ODS's) could be consistently excited with changes in drive point and only by excitation occurring at the corner locations.

(iii) Multiple excitation locations are required to obtain a complete modal model of the higher-order modes.

(iv) The membrane has stronger nonlinear response characteristics when excited near the edge of the membrane in a region that has lower stiffness than at other excitation locations within the body of the membrane.

(v) Many symmetric, realistic ODS's were identified from some tests with frequencies as high as 20 Hz. However, further work is needed to verify the accuracy of these results.

(vi) The three dominant mode natural frequencies increase with increasing membrane tension load at approximately the same rate and in an approximately linear fashion.

(vii) Preliminary results indicate that direct membrane electrodynamic shaker excitation cannot properly excite any of the modes.

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